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Reliability of Surface Micromachined MicroElectroMechanical Actuators

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Abstract – This paper will review some of the investigations into MicroElectroMechanical systems (MEMS) reliability. It will categorize the major reliability issues of MEMS actuators. Reliability concerns of stiction, mechanical wear, fracture, fatigue, shock, and vibration will be discussed.

I. INTRODUCTION

Reliability studies and predictions are becoming crucial to the success of MicroElectroMechanical System (MEMS) as commercial applications are developed. There have been extensive reliability studies by Maudie et al. identifying possible failure mechanisms in MEMS pressure sensors [1] and sensors exposed to harsh environments [2]. The lifetime experiments of Texas Instruments' Digital Micromirror Device (DMD) investigated unique failure mechanisms [3] resulting from fatigue, fracture, and environmental conditions of temperature and light intensity. However, most of the MEMS products on the market are sensors (pressure, acceleration, and chemical) that do not have rubbing surfaces. In both sensors and the DMD example, issues like friction and wear are minimal.

For MEMS actuators, normal operation requires surfaces to come into contact and rub against one another. In these cases wear of the rubbing surfaces becomes a reliability issue.

Clearly, there has been a significant amount of work in MEMS actuator reliability, but there is much more work to do. The following sections will describe some of the unique reliability issues associated with MEMS. The issues of stiction, mechanical wear, fracture, fatigue, shock, and vibration will be addressed.

II. STICTION

Stiction is one of the largest reliability issues today, affecting both sensors and actuators. Stiction is a general term describing the adhesion of the microstructure to adjacent structures.

Surface micromachined MEMS are mechanical structures fabricated from deposited thin films. The structures are encased in sacrificial layers (typically SiO_2) until ready for use. The oxide film is etched by hydrofluoric acid (HF) to yield a "released" sample. There are several strong adhesive forces that act on the structures during the drying stage of the release [4]. These include capillary, electrostatic, and van der Waals forces. Capillary forces dominate at these dimensions and processes have been developed to reduce or eliminate the forces for successful operation of MEMS structures [5].

Stiction can be prevalent after the release process, which will be manifested as low yield. Additionally, stiction can arise during use due to overdriving electrical signals, change in environment (high humidity or shock), or mechanical instabilities at resonance [6**]**.

Coupling agent coatings such as alkysilanes have been used to increase the hydrophobicity of the polysilicon surface, thus eliminating capillary forces [7]. The most studied silane coatings deposited on silicon are octadecyltrichlorosilane (OTS) precursor molecules having a chemical formula of $C_{18}H_{37}SiCl_3$. Additionally, a fluorinated chain, perfluorodecyltrichlorosilane (FTS, $C_6F_{13}CH_2SiCl_3$), has been studied by Alley et al. [8]. Application of a coupling agent requires preparation of the polysilicon surface by an oxidation step (H_2O_2), resulting in an oxide layer a few nanometers thick.

An alternate approach to applying a coupling agent prevents the formation of a meniscus by eliminating the liquid phase in the drying process as in Figure 1. The two methods are supercritical CO_2 drying ($SCCO_2$) [9] and freeze sublimation [10]. Both have been successfully applied to surface micromaching.

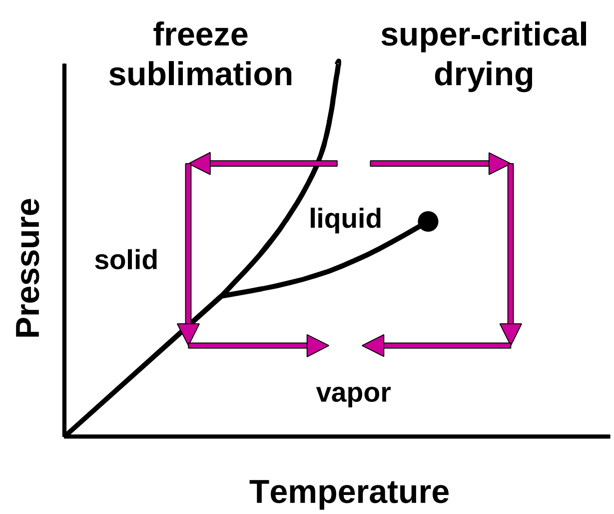

Figure 1. These two methods prevent the formation of meniscus by avoiding the liquid phase.

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Senft [11] performed friction tests on $SCCO_2$ processed devices and OTS-coated devices. The measured coefficient of friction was the same, but the OTS-coated devices ran three times longer implying better reliability. Additionally, work by Srinivasan et al. [12] suggests that nanometer thick surface treatments can act as a boundary lubricant and reduce the dynamic COF between OTS or FTS-coated polysilicon surfaces.

An empirical stiction-prediction methodology was developed for accelerometers prone to stiction failures due to shock [13]. This sensor was horizontally activated but sensitive to stiction in the vertical direction. The methodology successfully predicted the probability of vertical stiction as a function of applied g-level shock.

An example of a well-studied actuator is Texas Instruments' DMD projection system, which has an array of 500,000 individually addressable micromirrors (pixels) [14]. A drawing of two DMD pixels that act as a light switch is shown in Figure 2. The MEMS structure is fabricated over CMOS memory cells that control the rotation of the micromirror through electrostatic attraction. When the mirror rotates to +10 degrees, the light enters the projection optics producing a bright pixel (on state), alternately, a –10 degrees produces a dark or off state.

Reliability concerns [3] of the DMD system include the obvious defect of a stuck (nonfunctional) mirror. The three most likely conditions found to contribute to stuck mirrors were particle contamination, surface residue, and capillary condensation. Particles were the number one contributor to nonfunctional mirrors. The particles could either be on the surface of the mirror or under the mirror. The second cause of stuck mirrors was attributed to surface residue that increased the surface adhesion. An innovative approach to overcoming this surface adhesion was the incorporation of springs in the landing tips of the mirrors in addition to using a surface coating on the landing surface. This spring stored energy that pushed the mirror tip off the surface, and the surface coating reduced adhesion and capillary condensation.

MEMS devices that are typically prone to stiction problems are switches and relays [15, 16, 17]. Because surface coatings are insulating, switch contacts were developed using metallic materials. Schlaak et al. [18] found that although gold contacts provide the lowest contact resistance, they tend to stick due to high adhesive forces. An electroplated $AuNi_5$ contact had better properties and produced lifetimes of over 6 million cycles. Elsewhere, switch lifetimes of over 10^5 have been reported [19, 20].

III. Mechanical Wear

One of the first experiments to show wear as a dominant failure mechanism ran polysilicon microturbines [21] and gears at rotational speeds up to 600,000 rpm [22]. A focused air jet directed at the turbine induced the rotation. Gabriel et al. [21] estimated dynamic coefficients of friction between polysilicon and silicon ranging in value from 0.25 to 0.35. The wear was extensive enough to cause misalignment followed by wedging of the device.

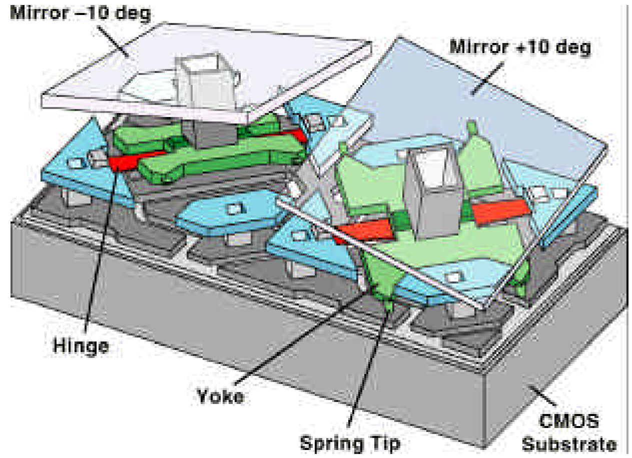

Figure 2. Two DMD micromirrors showing the on (+10 degrees) and off (-10 degrees) state. The mirrors, shown as transparent are actually highly reflective. (*Image courtesy of Texas Instruments)*

In another experiment, microfabricated radial-gap electric motors were tested in room air at speeds between 200 and 2000 rpm [23]. Lifetime was limited by wear to 10,000 cycles. This experiment incorporated a silicon nitride film in the bearing and measured a coefficient of friction of the nitride-polysilicon bearing to be 0.36. Scanning electron microscopy (SEM) analysis after failure revealed wear particles on the friction bearing surfaces.

Extensive reliability work [24, 25, 26, 27] has been performed on the Sandia microengine [28]. The microengine consists of orthogonal linear comb drive actuators mechanically connected to a rotating gear as seen in Figure 3. By

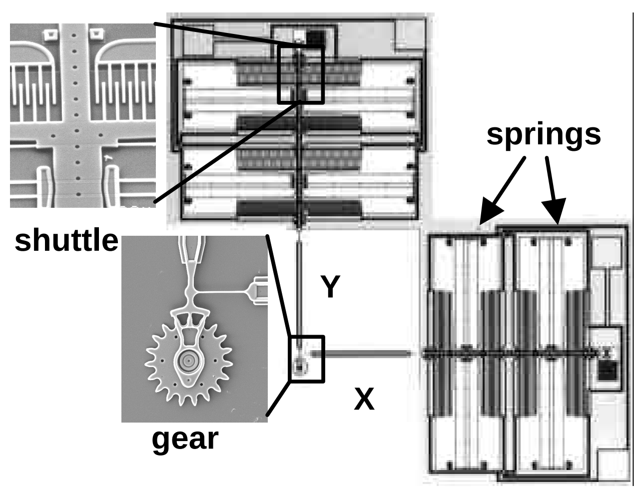

Figure 3. Sandia microengine with expanded views of the comb drive (top left) and the rotating gear (bottom left).

applying model-based voltages, the linear displacement of the comb drives was transformed into circular motion [29]. The X and Y linkage arms are connected to the gear via a pin joint. The gear rotates about a hub, which is anchored to the substrate.

A. Frequency

Experiments on the lifetime of a surface-micromachined microengine investigating frequency dependence revealed wear as the dominant failure mechanism [24]. The Sandia High Volume Measurement of Micromachine Reliability (SHiMMeR) [25] tester was used to provide electrical signals to large numbers of packaged microengines and to optically inspect them for functionality. Microengines driving large load gears, as in Figure 4, were stressed at various frequencies. In order to accelerate the failures, a large tangential force (factor of 5 times normal operating) was applied to the gear through the pin joint.

Severe drive pin wear and occasional breakage of drive pins were characteristic of these devices when tested to failure. An example of such wear is seen in Figure 5, where the bore of the hole in the drive gear which accepts the drive pin is shown after a pin has been broken. This wear has produced an out-of-round shape both by wearing material away and by depositing debris on the side wall of this hole. For comparison, a similar hole is shown from a control sample with similar processing history that was not stressed.

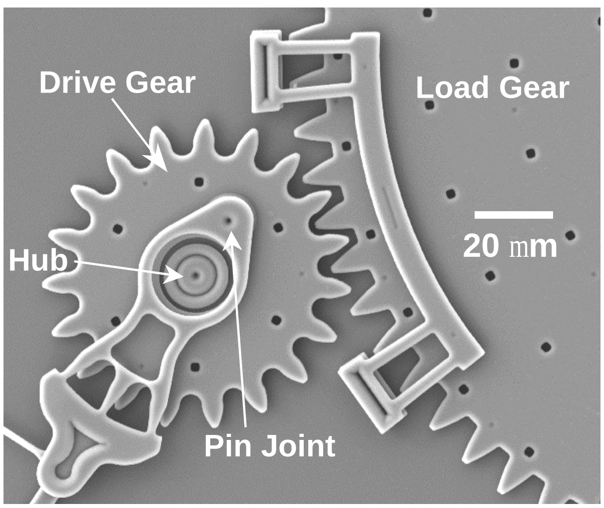

Figure 4. SEM image of a microengine gear driving a large load gear. The hub is anchored to the substrate. The pin joint attaches the drive linkages to the gear.

The behavior of the microengines as they were stressed followed a consistent pattern. Initially the microengines ran smoothly. With the accumulation of stress, the operation of the microengines became sticky and jerky (stick-slip behavior) at inspection frequencies. Some of the microengines would actually work through the sticky behavior and become smooth again. Near the end of life, the rotations became more erratic until the microengines failed by sticking or rocking back and forth through a small angle. In this work, the stickiness of the gear motion was presumed to be due to the interaction of asperities on the rubbing surfaces. Asperities could break off causing wear debris or adhere which would result in a seized gear.

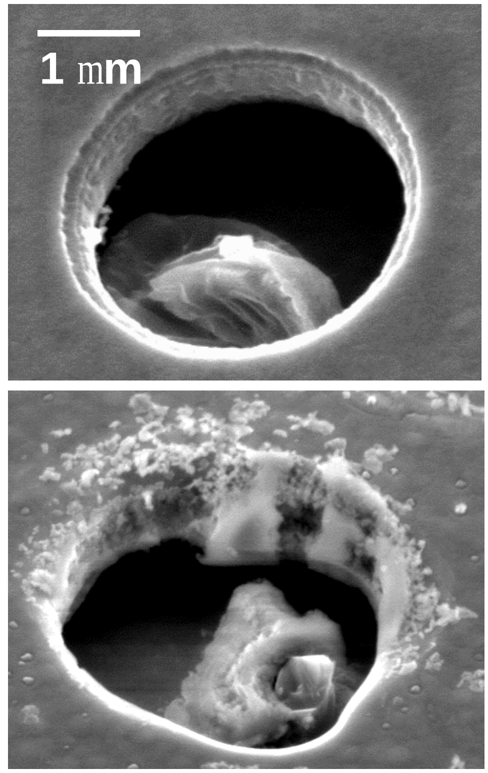

Figure 5. SEM image of the wear in the pinhole (pin joint resides) of the drive gear is shown in the bottom image. The top image was from the control sample.

The median cycles to failure ranged from 10^5 to 10^6 with several microengines reaching close to 10^9. A predictive reliability model for the microengine was developed [23], which was based on the fundamental principles of the physics of wear in a mechanically resonating system. The complete description for the reliability of MEMS actuators failing due to wear, where R_f represents the median number of revolutions to failure is

$$R_f = \left(\frac{1}{2p}\right)\left(\frac{1}{c}\right)\frac{V_c}{rF_n}\left[\sqrt{\left[1-\left(\frac{w}{w_o}\right)^2\right]^2+\left(\frac{1}{Q}\frac{w}{w_o}\right)^2}\,\right]$$

In this equation, c is a variable that is directly proportional to the wear coefficient and inversely proportional to the hardness of the material. V_c is the critical volume necessary to seize the microengine, r is the radius of the pin joint, and F_n is the nominal force applied to the joint. The term in large square brackets represents a "magnification factor" caused by approach to resonance, Q is the quality factor of the damped harmonic mechanical system, and w/w_o is the ratio of the driving frequency to the resonant frequency of the system.

Using the variable for adhesive wear, $\boldsymbol{c = K/9\, s_{yp}}$, for polysilicon yields the graph in Figure 6. K is the adhesive wear constant and s_{yp} is the uniaxial yield strength for polysilicon.

There are two important characteristics in the data versus model comparison. First, the agreement supports the conclusion that the failures are associated with wear and not some other physical mechanism. However, the specific wear mechanism or combinations of mechanisms are as yet undetermined. Second, the functional dependence is correct, with the model clearly predicting the decrease in the number of revolutions to failure around the resonant frequency and the increase in the number of revolutions to failure above resonant frequency.

In another study of the microengine, it was determined that the introduction of an additional source of rubbing surfaces (in this case, a dimple rubbing against a shuttle) reduced the lifetime and thus, the reliability of the microengine [27].

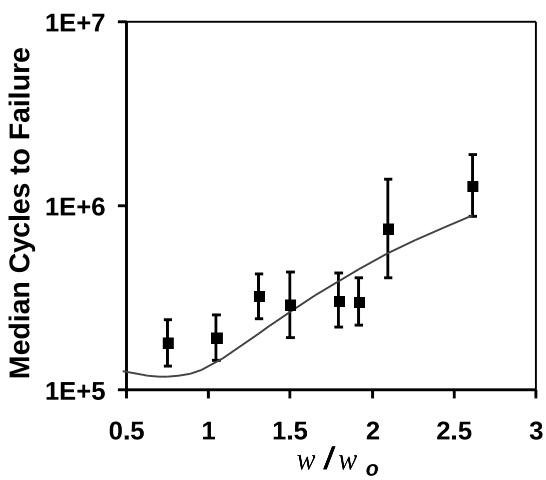

Figure 6. Data vs. predictive reliability model shows good agreement.

B. Humidity

Humidity has been shown to be a strong factor in the wear of polysilicon surfaces [30, 31]. Microengines (Figure 3) were stressed at 1720 Hz at various humidity levels and two surface treatments, FTS coating and super critical CO_2 drying. In order to accelerate the failures, a large tangential force (factor of 5 times normal operating) was applied to the gear through the pin joint.

The dominant failure mechanism for these microengines has been identified as wear. The major effects of the wear process were either pin joint wear-out causing the linkage arm to break away from the gear or accumulation of wear debris causing the microengine to seize. The overwhelming effect of the humidity was demonstrated by the amount of wear debris observed. The volume of debris increased dramatically as we lowered the humidity. This is shown in the comparison of two humidity levels in Figure 7. The bottom gear was stressed at 1.8 % RH at 25 ^{o}C and the top was stressed at 31% RH at 25 ^{o}C. Both failed after roughly 600,000 cycles, but the wear debris covers the entire face of the lower humidity test.

These experiments have shown that wear of the polysilicon surfaces contributed to the failure of the microengines.

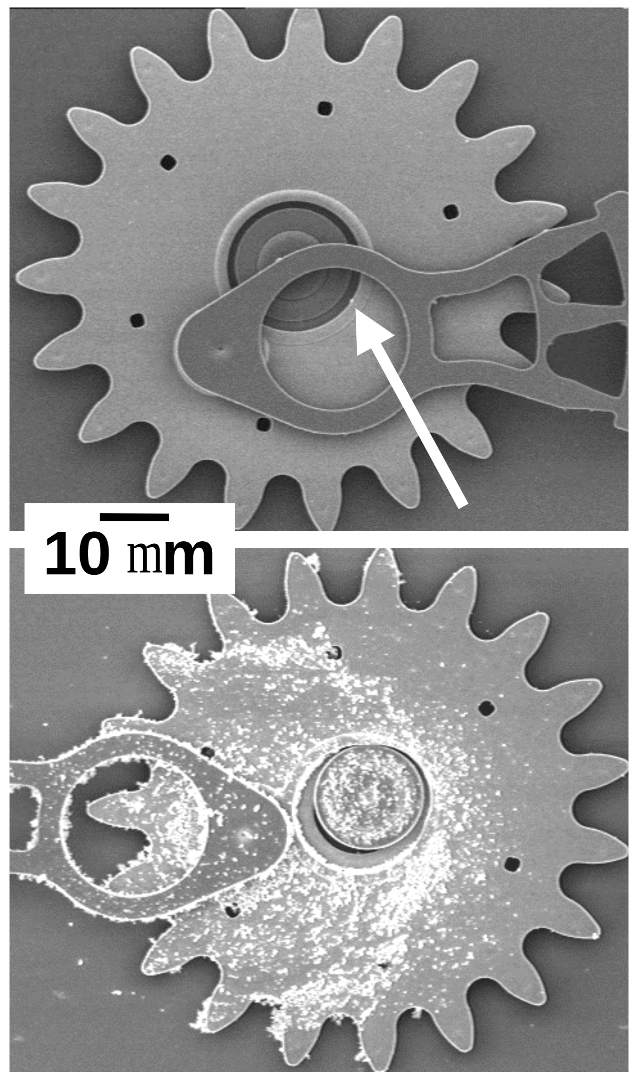

Figure 7. The top SEM image shows the lack of debris accumulation of the microengine drive gear after running in a high humidity (31% RH) environment. The bottom image shows the debris accumulation of the gear after running in a low-humidity (1.8% RH) environment. Both accumulated roughly 600,000 cycles before failure.

Performing the experiments in air with varying humidity introduced effects due to different surface reactions into the friction and wear study. Chemical interactions as a result of rubbing are referred to as tribochemistry and tribochemical reactions influence friction coefficients as well as wear mechanisms and wear rates [32].

To estimate the wear volume of material one can measure the missing volume in the worn device. A focused ion beam (FIB) was used to cut through the hub and pin joint. The cross sections revealed areas of worn volume and wear debris.

The locations exhibiting the most wear were the hub and pin joint areas so estimates were made there. The technique assumes that the wear is symmetrical around the hub and pin joint. The error was estimated in the technique as ± 20% of the calculated worn area. The wear volume was normalized by the total number of cycles to failure to yield wear rate which is shown in Figure 8 as a function of % RH at 25°C.

This wear of polysilicon can be compared to other silicon ceramics. The data shown in Figure 8 agree with studies of a SiC/SiC system [33] where the decrease in wear rate has been attributed to a tribochemical reaction leading to the formation of a protective film of hydrated amorphous silica. Silicon nitride sliding on silicon nitride was also investigated [34] and the main mechanism of wear was the tribochemical oxidation of the silicon nitride to form silicon oxide. The wear rate increased in drier conditions in the silicon nitride case also.

It was shown that the amount of wear debris generated in sliding micromachined polysilicon surfaces is a function of the humidity in an air environment. As the humidity decreases, the volume of wear debris generated increases. For the higher humidity levels, the formation of surface hydroxides acts as a lubricant, resulting in lower amounts of wear debris [35, 36, 37]. At lower levels of humidity, 1.8% and 10% RH, formation of hydroxides is reduced, resulting in large amounts of wear debris.

The wear debris was identified as amorphous oxidized silicon, both in small and large agglomerates, by the use of both transmission electron microscopy and electron diffraction analysis. **No** polysilicon was observed in any portion of the wear debris indicating that the surfaces were oxidized before the wear particles were generated.

The $SCCO_2$ treatment process produced microengines that were less reliable during operation than microengines with the FTS treatment, which can be attributed to the FTS film acting as a lubricant.

Overall, wear of rubbing surfaces has been one of the fundamental failure modes associated with MEMS. Prevention of wear certainly seems like a good investment and many researchers are investigating lubricants. Henck [38] documented the successful approach used by TI's digital micromirror device.

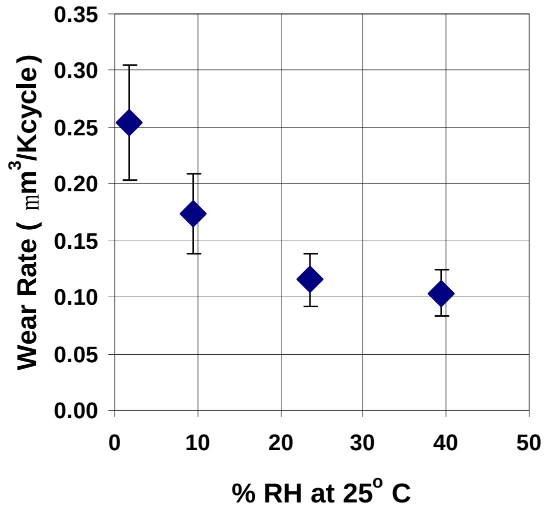

Figure 8. This plot of wear rate of FTS-coated microengines as a function of humidity shows the increase in wear rate as humidity decreases.

IV. Fracture and Fatigue

Characterization of MEMS mechanical properties is essential in predicting fracture or fatigue of devices. Sharpe et al. [39] has measured the thin film properties of Young's modulus (169 ± 6 GPa), Poisson's ratio (0.22 ± 0.011) and tensile strength (1.20 ± 0.15 GPa) for polysilicon. Greek et al. [40] developed a method to implement tensile tests in situ on micromachined structures.

Many complex MEMS devices have been fabricated out of polysilicon [41, 42]. It is a strong, hard, yet brittle material, but fracture (without wear) has **not** been observed [43] in MEMS devices fabricated using the SUMMiT process [44] at Sandia National Labs.

Brown et al. [45] have developed the resonant fatigue test structure shown in Figure 9. The stress concentrator, or notch, circled in the figure is designed so that the specimen is broken at resonance. The fatigue response can then be measured by exciting the specimen at some fraction of the resonance frequency and measuring the number of cycles to failure. A more complete discussion of this work is presented by Muhlstein et al. [46].

Douglass [3] reported that Texas Instruments' DMD hinged mirrors (aluminum) have demonstrated 1.7 x 10^{12} mirror cycles with no hinge fatigue failures. They estimate that for a reliable product, each mirror element must switch more than 90 x 10^9 times. TI did uncover a hinge memory failure mode where the mirror would not return to the rest position. The root cause was metal creep and improvements in the hinge material increased robustness of the product.

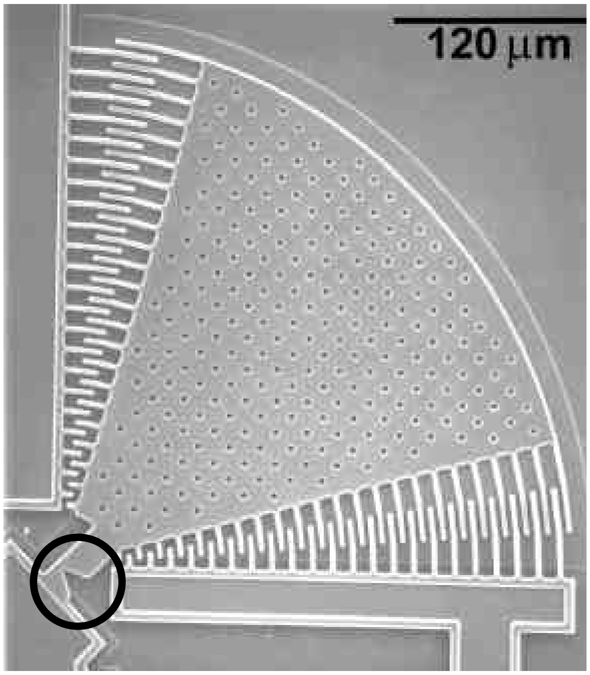

Figure 9. Resonant fatigue specimen with stress concentrator circled. *(Image courtesy of Muhlstein at E^x^ponent, Failure Analysis Associates)*

V. Shock and Vibration

Brown et al. [47] documented work that demonstrates the ruggedness of MEMS devices. Artillery projectiles and rockets instrumented with MEMS accelerometers were flight tested with good results. Products from Analog Devices, Motorola, and Endevco were attached to a 155-mm artillery shell. All sensors survived and data from the ADXL05 are shown in Figure 10. The apparent noise in the figure is actually data from the spin precession and nutation of the projectile. Ground tests included shock table drops and air gun launches. Some of the sensors survived up to 95,000g.

Douglass [3] reported that Texas Instruments' DMD hinged mirrors (aluminum) exhibited robustness to shock, vibration, and acceleration. The micromirrors resonate at frequencies greater than 100 kHz. Normal handling and dropping occurs at frequencies less than 1000 Hz so no resonance modes are excited.

VI. Conclusions

Some of the major MEMS concerns have been addressed in this review. The major concern for these small devices is stiction, which affects yield and reliability. Wear and the resulting adhesion that causes failure has been shown to be a dominant reliability issue. Fracture has not been observed much, but the work to characterize materials properties is

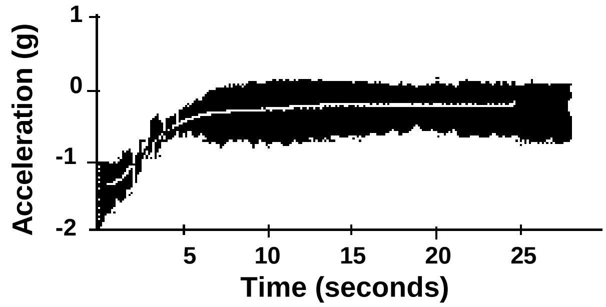

Figure 10. Acceleration profile for an ADXL05 sensor launched from a 155-mm artillery shot. The apparent noise is actually data from the spin and yaw of the projectile. *(Data courtesy of Brown at Wright-Patterson AFB [46])*

essential to provide values for design calculations. Fatigue is not an issue as of yet for polysilicon, but it may be a concern for other materials. MEMS devices have demonstrated robustness to shock and vibration, although combinations of effects (e. g. out-of-plane shock which causes stiction) may indeed be a concern.

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